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SAR Interferometry applications on active volcanoes: state of the art and perspectives for volcano monitoring(*)

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Summary. — In this paper the application of the Synthetic Aperture Radar Interferometry (INSAR) on volcanology is analysed. Since it is not a real novelty among the different applications of INSAR in Earth Observation activities, at the beginning of this paper we analyse the state of the art of the researches in this field. During the discussion, the point of view of volcanologists is favoured because it is considered that the first applications were often badly aimed. Consequently, the initial INSAR performances in volcanology were overrated with respect to the real capabilities of this technique. This fact lead to discover some unexpected limitations in INSAR usage in volcano monitoring, but, at the same time, spurred on scientists to overcome these drawbacks. The results achieved recently allow to better apply SAR to volcanology; in the paper a possible operative work-plan aimed at introducing INSAR in the volcano monitoring system is presented.

PACS 91.10.Fc – Space geodetic surveys.
PACS 91.10.Jf – Topography; geometric observations.
PACS 91.10.Kg – Crustal movements.
PACS 91.40 – Volcanology.

1. – Introduction

Since the first applications of SAR differential interferometry to survey the Earth surface [1], volcanoes have been proposed as suitable testing and application areas at least for two reasons: they are usually high standing above the surrounding areas (allowing an easy recognition of their features) and, if volcanic activity occurs, they are subject to changes in their *shape and/or surface* (using the word *change* in the widest sense to identify any effects of the volcanic activity). As the interferometric processing techniques became reliable, scientists envisaged that the INSAR should be able to detect *changes* ranging from few centimetres to metres, using different algorithms to measure *changes* of

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different orders of magnitude [1-5]. However, because the interferograms are the prime observable, we can use only the INSAR term to identify such kinds of approach, even if sometimes other terms have been associated to particular techniques (*e.g.*, DINSAR for Differential SAR Interferometry to identify the double difference interferogram described by [1]). Certainly these *changes* encouraged the engineers to use SAR Interferometry on the volcanoes, believing that it would be able to make measurements from space without ground control [2] and furthermore neglecting that these changes imply complex geological phenomena with different sources, magnitude and extension. However, as a consequence of this early interest, a large amount of data have been taken on volcanoes (such as Etna, Kilawea, etc.) both during experimental (*e.g.*, Shuttle SIR-C/X-SAR) or routinely space missions (*e.g.*, ESR1/2) (*e.g.*, [6-8] and a rapid introduction in the routine use of SAR in volcano monitoring was envisaged. At the same time, many works, mainly aimed at optimising the interferometric processing from the computational point of view, include this challenge in their objectives. However, since they have been carried out overlooking the volcanological constraints and undervaluing the source of error and bias, they lead scientist to overrate the expected applications. As a consequence, the first volcanological applications of INSAR found both new results but also encountered unexpected problems; for instance, they have limits on the real capability to measure the new volumes of volcanic products, or they met significant discrepancies between the results of INSAR and ground-based geophysical studies. These facts suggested research on the effects of the source of error and bias on the interferograms, discovering that they could be induced exactly by the peculiarities of the volcanoes (its topography and the altitude). Now the knowledge and the managing of these sources of error seems largely to have improved the possibilities to introduce the INSAR in the volcano monitoring system, but at the same time, a careful use to investigate *changes* caused by different phenomena is required.

On an active volcano, indeed, large surface changes occur near the active craters and are related to phenomena such as the growth of pyroclastic cones, collapse of craters, openings of new eruptive vents, emplacements of new lava flows and domes. Such changes, which can be qualified as *topographic*, are usually detected during geological surveys and broadly quantified since they are so great in magnitude that they do not require high precision (*e.g.*, the areas covered by a new lava flow surface is in the order of $10^6\,\mathrm{m}^2$, but its estimation is usually performed with an order of the accuracy not greater than $10^3\,\mathrm{m}^2$). Besides topographic changes, those phenomena more appropriately named *ground deformations* have also been included in the *shape changes* concept (even if sometimes with the adjective *subtle*; [2]). They are often due to the magma movements within the plumbing system of the volcano, but also to other phenomena such as fault movements, lava flow cooling or, in some case, landslides movements. Those changes are so small in magnitude with respect to the previous ones that in the classical geophysical studies they require precise instrumentation to be detected and quantified (*e.g.*, levelling, EDM or GPS surveys). The attempt to study, using INSAR techniques, this mixing of phenomena together probably led to the above-mentioned poor application of the INSAR interferometry in volcanology.

In the following two sections the state of the art of the INSAR application in studying/monitoring the two classes of phenomena will be discussed separately. In sect. **2** we address those give rising to topographic changes in the shape of the volcanoes, while the application of the INSAR on the ground deformations studies will be discussed in sect. **3**.

2. – Topographic use of INSAR

Before proceeding with the analysis of the application of INSAR on the topographic surveys of volcanoes we have to answer to the following questions.

What are the uses of Digital Elevation Models (DEM) on active volcanic areas?

What are the advantages of introducing the INSAR techniques to obtain DEM of volcanoes?

There are at least three possible fields of interest in the use the DEM on volcanology: to use it in modelling researches (*e.g.*, computation of path of new lava flows, modelling of ground deformation taking into account the topography, etc.) (*e.g.*, [9, 10, 7, 11, 12]), to quantify topographic changes due to volcanic activity (usually the volume of new lava flows; *e.g.*, [13]) and to carry out geological mapping and geomorphological studies on volcanic edifices (*e.g.*, [14,15]). Each of the above-mentioned topics requires different kind of data and appropriate survey approaches: only one DEM is needed for the modelling and geological researches, while multiple DEM are required to quantify the topographic changes due to volcanic activity. At the same time, also the accuracy is different between the three topics; in general it should be said that the minimal accuracy to obtain a worthy result diminishes from the first kind of application toward the third. Bearing in mind these aims, several DEM have been produced for volcanic areas using INSAR. The first examples are relevant to surveys carried out by airborne TOPSAR flights in 1993 over some super-sites of the SIR-C/X-SAR missions: they refer to Vesuvius [7], Fernandina Island (Galapagos, [16]), and Kilawea (Hawaii, [13]). A further DEM was produced on the top of Mt. Etna, using airborne SAR data, during an experiment carried out by the DLR airborne E-SAR system [17]. During the SIR-C/X-SAR missions in 1994, several volcanic areas were surveyed (*e.g.*, Etna, Vesuvius, Kilawea, etc.) but the only available DEM have been obtained in the framework of more complete morphological and/or geophysical studies carried out on Mt. Etna and Kilawea [14, 4]. The relatively scarcity of DEM obtained from Shuttle missions might be due to the difficulties to obtain them due to the high uncertainty of Shuttle orbits and, consequently, of interferometric baselines, as emphasised in [6]. The mission of ERS1/2 routinely carried out since 1992 has allowed the production of DEM over volcanic areas, such as for Mt. Etna [18, 19].

These experiences assessed the accuracy of INSAR DEM obtained using different techniques. Single-pass airborne INSAR-derived DEM have a spatial resolution ranging from 5 m (E-SAR) to 10 m (TOPSAR); vertical accuracy range from 1–2 m, resulting from TOPSAR experiments over relatively “flat” basaltic surfaces [13], to 8–9 m, obtained by the E-SAR fly over the top of Mt. Etna [17]. The double-pass spaceborne INSAR interferometry, using ERS1/2 data, produced DEM having spatial resolution in the order of 25 m and vertical accuracy between 13 m and 4 m, as recently assessed on Mt. Etna test site by using DEM produced by independent approaches [18, 20, 19]. However it must be stressed that these high-accuracy ERS-based models are obtained appropriately merging the information coming from several interferometric pairs, both ascending and descending; this means that these DEM are obtained from SAR passes spanning from months to years and so, the use of these approaches is advised for monitoring dynamic phenomena.

Obviously, the INSAR is not the only technique that produces DEM, but its advantages with respect to the geodetic or photogrammetric techniques are their capability to both i) carry out surveys in any weather conditions and ii) cover large areas at relatively low *costs*. Here term *cost* is used in the broad sense, including both the financial cost, strictly speaking (*e.g.,* to buy or get the data) and the time required to obtain the final product (collection of data and processing). Until the end of the 80's the DEM suitable for many volcanic areas were produced using classic geodetic or photogrammetric surveys whose final accuracy (both in planar than in vertical co-ordinates) is comparable or, in some case, worse than those obtained from spaceborne or airborne INSAR. For instance, the vertical resolution is probably in the same order of magnitude for both kinds of DEM, but the advantage of the INSAR DEM is the capability to maintain the information about the features whose "roughness" is equal to the scale of the spatial resolution; this information is lost, masked by artefacts or, at best, smoothed in the photogrammetric or geodetic DEM because they are produced by using interpolating techniques [14]. These considerations made the INSAR derived DEM more advantageous, at least for the geological researches, than the geodetic DEM, as confirmed by several studies (*e.g.*, [14, 13]). Furthermore, the capability of the SAR data to provide both topographic and back-scattering (using amplitude and coherence images) features of the terrain allow to carry out classification and morphological analysis on the same data set [14] avoiding errors introduced by a bad co-registration between different data sources.

The recent introduction of the digital photogrammetry changed the result of the comparison and now it is possible to obtain high-accuracy DEM (about two orders of magnitude better than the INSAR) for relatively small areas, even if the high "cost" (again in the same sense as used above) remains the main limitation to its application on large areas [21].

As a consequence, at this moment the only unquestionable advantage of the INSAR with respect to the digital photogrammetry is restricted to the possibility to operate daytime or night time in any weather conditions, but its effective use should be addressed to the aim of the specific application (*e.g.*, how large is the area where new lava flow path have to be computed? how much time is required to produce the DEM?).

However, apart from these limitations, another question arises from the analysis of the published papers. Why are the applications aimed at detecting or measuring or monitoring topographic changes on volcanoes so few compared to the large number of volcanoes that have been active during the last decade (*i.e.* when the space-based SAR missions have been routinely carried out)?

Even though it is beyond the aim of this paper to discuss in detail the wide range of volcanic phenomena producing topographic changes, their short introduction is needed in order to define the required accuracy of the DEM. These phenomena could be divided into those producing growth (lava flows or dome emplacements, pyroclastic cones growth) and those engendering collapses (crater widening, pit craters formations, step wall collapse).

These latter usually produce morphologies with very steep surfaces, which cannot be recognised by SAR due to layover/shadowing effects; in this case the use of INSAR is eventually restricted to bound the area affected by the phenomenon.

The addition of new material on the volcanoes surface is certainly the main effect of the volcanic activity. The orders of magnitude of the altitude variation range from a few centimetres, in the case of distal pyroclastic fall deposits, to meters, in the case of lava flows, to hundred meters, in the case of domes or pyroclastic cones. Disregarding the phenomena bringing about a few centimetre variations, we will now look in more detail at the others.

With regard to the domes, they are often unfortunately located within and/or close to sites with very steep topography (craters) thus making very difficult for their recognition. Furthermore, the domes themselves are very hard to identify in the interferograms because both their surface remains very unstable for a long time (producing a loss of coherence for two pass interferometry) and/or so steep that again the problems due to the layover/shadowing effects prevent any survey. These drawbacks relevant to dome monitoring are confirmed by the experience achieved on the recent eruption occurring at Soufriere Hills Volcano, Montserrat, using RADARSAT data [22]; this eruption has been studied using only a multitemporal analysis of the amplitude data, which allows a temporal reconstruction of the volcanic event, but did not produce any volume calculation.

Also the quantification of the pyroclastic cones using the INSAR is unlikely to be achieved due to the average angle of their flanks that is always more than 20–25 $^\circ$, close to the range of variation of the incidence angle for several radar systems (*e.g.*, ERS1/2). The quantification of the volume of new lava flow remains the most promising field of application for INSAR topography, but its main limitation concerns its accuracy. Even in the optimal conditions and assuming that the volume estimation is not aimed at monitoring any dynamic phenomena but only to get data at the end of the studied eruption, the satellite-borne SAR-derived DEM cannot provide vertical variation as accurate as 10–20 m. This error is in the same range of the mean thickness of lava flows and thus makes these products unavailable for routine works and limits its field of application to large eruptions.

3. – Ground deformation from INSAR

It has been well known for long time that the intrusion of magma bodies in the uppermost part of the Earth's crust or the emptying of magma reservoirs produce ground deformations. The first well-documented ground deformations date back to the beginning of this century: eruptions of Sakurazima Volcano, in 1914, and Kilawea, in 1924 [23]. During the time, several experimental and theoretical researches have been performed aimed at improving the knowledge on the relationship between these events and the volcanic activities. In these researches all the geodetic techniques developed in the last four or five decades have been introduced to measure ground deformations as completely and accurately as possible. The GPS is the most recent and suitable technique adopted to measure ground deformation but, like the other geodetic ones, it provides spot data, *i.e.* they are relevant to network vertices whose number rarely exceeds the order of tenths in areas of hundreds, often thousands, square kilometres. The SAR allows to get data continuously on the surface and thus, even if with an absolute accuracy lower than the GPS, its introduction has been seen as the only way to continuously map the horizontal gradients of ground deformation patterns.

However, the comparison between the results of the first applications of INSAR in volcanology (*e.g.*, on Etna; [8]) and the other geophysical and volcanological studies carried out around the same volcanic events highlighted discrepancies in the main characteristics of the deformation sources (depth, locations, magnitude, etc.) obtained starting from the different data set [24-26]. Even if both INSAR and GPS (or other geodetic techniques) provide measurements of the ground deformation pattern, they have indeed several differences that could produce these discrepancies, such as, for instance, differences in accuracy, in the kind of data (mono-dimensional, in line of sight, for the SAR and three-dimensional for the GPS), in the number of samples of ground deformation patterns (very large for the INSAR with respect to the GPS), in extension of investigated areas (usually larger for the INSAR with respect the GPS), in techniques used for data inversion. Starting the discussion from this last difference could help us to better understand how the combination between these differences could produce the above-mentioned discrepancies.

The inversion of ground deformation data is a process aimed at determining the parameters of a specific ground deformation source from the data collected in the field. It should be performed adopting several strategies, but the generalised least-square methods or the numerical approaches (like simplex, neural networks, simulated annealing, etc.) are the most commonly used. In any cases these strategies are adapted to use the relatively low number of geodetic data. The introduction of SAR data changes not only the number of data that should be inverted but also the "quality" of these data. They are mono-dimensional and, furthermore, their quality changes widely across the interferogram, as is well visualised by the coherence maps. These facts, for example, largely reduce—or in some case prevent—the possibility to use the least-square approach conventionally adopted to invert geodetic data. In fact, the first and more classical examples of application of INSAR techniques in studying ground deformation data used relatively simple data inversion techniques. For example, for Etna [8] a trial and error approach has been used, while for Landers earthquake [27] the technique adopted was to fix the geometry of the source and to determine only the motion, with a simple linear model. Obviously, it is not always possible to simplify the problem in order to attempt to use least-square approaches. Since these problems are highly non-linear, the crucial point of the inversion process is the suitability of a robust optimisation strategy in finding the minimum of any function linked to differences between observed and modelled observations. For instance, [26] revealed how the introduction of more sophisticated methods (*e.g.*, the Monte Carlo method like those adopted by [28]) improved the comparison between sources deduced from geodetic and INSAR data.

Furthermore, on volcanic areas the line of sight geometry of the SAR could make the modelling a difficult task, due to the peculiarities of the ground deformation sources usually chosen to describe the magma reservoirs in the volcanoes. Whichever particular model we used (*e.g.*, [23, 29, 30]) it is typically axisymmetric. The large number of practical examples shows that, even in the non-isotropic cases (like [29]), one of the axes of symmetry is generally vertical and thus orthogonal to the Earth surfaces (which is the reference surface over which the expected displacements are computed). Dieterich *et al.* [31] proved, by using a forward numerical approach, that in such conditions, the vertical displacements alone are not able to fully describe the ground displacement patterns, because the variability across the reference surface of the synthetic ground deformations shape is subtle "and may be somewhat misleading". This study concludes that "it may be difficult to arrive at a moderately reliable estimate of reservoir geometry and depth using vertical displacement data alone." Since i) the line of sight and the vertical components of displacement are similar both in direction and magnitude and ii) the INSAR ground deformation patterns are relative measurements and not absolute (thus it cannot be possible to take advantage from the absolute maximum magnitude of the vertical displacement), then we can extend these considerations also to the case of the SAR and we can conclude that axisymmetric sources obtained using INSAR data should be taken into account only after careful geophysical validation (fig. 1).

A further possible source of discrepancies between geodetic-based and SAR-based volcanic sources has been recently assessed by the authors of ref. [10] who observed, by using forward numerical models, that the slopes of volcanoes change the theoretical ground deformation patterns leading, for the steepest edifices, to the sources obtained from INSAR data to be deeper than the actual.

Somewhat related to the typically prominent topography of the volcanoes is also the effect of the atmosphere changes between two SAR passes. Actually, this source of error has been identified since the first application of the interferometry (*e.g.*, [3, 5]) but, at that time, its importance was postponed with respect to that of other source of errors

Fig. 1. – Examples of line of sight displacements, shifted with respect to the minimum values, assumed as reference level. The displacements are computed for a set of Mogi sources located at different depths (f), having the same "strength" (10^{17} Pa m^3). The shear modulus is assumed equal to (30×10^9 Pa). The displacements are computed at radial distances from the centre of source proportional to its depth (f). The error bars are assumed equal to 1/4 of interferometric fringes for ERS1/2 system. From the plot, it is evident that except for the very shallow sources (curve with highest value), the displacements relevant to the other ones remain close or within the incertitude of INSAR measurements. This fact might weaken the reliability of the inversion of experimental data.

(*e.g.*, that due to the baseline). As the number of applications increased, it becomes more and more evident that the effects of atmosphere are visible in the interferograms and consequently that this source of error cannot be neglected. In some cases these effects have been hypothesised as responsible for the disagreement between INSAR and GPS measurements [4]. These considerations suggested a number of studies aimed at characterising the atmospheric errors [32, 33]. These researches lead to the conclusion that, as concerning the geophysical applications: a) the troposphere is much more disturbing than the ionosphere; b) the changes in water vapour content are by far the main source of the tropospheric errors; c) large baseline lengths allow to greatly reduce the errors in topographic applications, while for ground deformation studies (and particularly for 2 pass interferometry) baseline dimensions are unimportant; d) these errors are well described by a Kolmogorov 8/3 power law spectrum, associated with air turbulence. The application of these conclusions on volcanoes with prominent topography lead to the conclusion that, since the water vapour contents changes with the altitude, as do the temperature and the pressure, the tropospheric delay is higher in the lower part of the volcanoes with respect to their summit. This effect could produce interferometric fringes (for instance, up to 3 on Etna; Bonforte *et al.* [34]) wrongly ascribed to ground deformations. To overcome this problem, approaches based both on the staking [33] or on the calibration [35, 36] are proposed. The former are based both on the availability of independent interferograms of the same area and on the assumption that no-deformation occurs between different stacked interferograms. This assumption, even though possible only in particular experimental conditions (*e.g.*, for the 2 day-shift for the SIR-C interferogram set used in [33]) is not usual when the 35-day repeat cycle of ERS2 satellite is used to monitor active volcanic areas. Thus, approaches based on the calibration of INSAR products using measurements carried out with independent sensors seem more suitable to routinely reduce the atmospheric effect. In this perspective, the atmospheric delay estimated by using theoretical models (*e.g.*, [37]) and measured by GPS data have been experienced [34-36].

4. – Towards the use of SAR in volcano monitoring

To monitor volcanic activity means to be able to follow the various phenomena as they occur in order to get all significant data suitable to fully describe them. To collect data after the phenomena occurred would not be enough to monitor it, though certainly it might allow to perform studies and assess models. Similar to all the geological systems, volcanoes are special laboratories where man cannot plan the experiments but he must always be ready to get the data with the appropriate frequency (both in time and space) and accuracy. These two considerations (that may appear trivial) are the ineluctable starting points to evaluate any technique candidate to monitor the volcanoes.

In fig. 2 and fig. 3 the main temporal and spatial characteristics of the evolution of the volcanic phenomena producing topographic changes (fig. 2) and ground deformations (fig. 3) are reported. The figures show the limits of the ERS1/2 system both in terms of

Fig. 2. – Time and space plot of various volcanic phenomena leading to topographic changes. The dimensions of the fields do not include the exceptional phenomena (see text for discussion).

Fig. 3. – Time and space plot of various volcanic phenomena leading to ground deformations (see text for discussion).

repetition cycle (35 days and 1 day for Tandem) and spatial resolution (25 m); the choice of this system is evidently performed on its capability to be operative which has been more thoroughly assessed with respect to the other systems (*e.g.*, RADARSAT, JERS).

From fig. 2 it is evident that only a few phenomena producing topographic changes could be monitored. Now, the question is to define an effective way to use the INSAR in order to overcome the difficulties in the topographic use of the INSAR on the volcanic areas. The possibility to monitor lava flows or domes by quantifying the volume of emitted lava by DEM comparison, while the eruption is flowing, is entirely prevented by the continuously changing in Earth's surface, producing loss of coherence between the interferometric pairs. However, precisely the exploitation of this effect could allow to map areas where the lava flows or the domes were moving between the two SAR passes, even if with the spatial resolution corresponding to the pixel dimension. Assuming an estimation of the thickness of the lava flow, it is then possible to perform an estimation of the volume. This possibility, even if it provides only rough quantitative information about the observed phenomena, could be particularly helpful in case of eruptions producing large compound lava fields (in the order of several square km). Zebker *et al.* [38] report an example of this kind of application on the active lava flows outpoured from the Pu'u O'o craters on Kilawea volcano. This use of the INSAR offers the opportunity to highlight the useful contribution that the coherence maps could make to geological studies of volcanoes through terrain classification. On Etna [14] and more recently on Erta'Ale (Ethiopia) volcanoes [39] it has been proven, by comparing geological and coherence maps, that it is possible to extract geological features from the interferometric products. Even if both these kinds of characterisation cannot be used for monitoring purposes because more accurate validation campaigns are still required to assess the real capability of such approaches, the coherence maps could represent a new tool for geological studies in remote volcanic areas.

Figure 3 highlights that monitoring ground deformation due to the emplacements of dykes or very shallow magma reservoirs is a hard task to be achieved, since these phenomena usually evolve in a very short time (from days until a few weeks). Analogously, the use of INSAR cannot be planned to monitor rapid movement along faults, like that occurring during earthquakes. Differently, ground deformation due to much deeper sources or continuous fault movements (like creeping phenomena) might be monitored; this puts the INSAR as a candidate to get data relevant to the dynamics of the volcano at mid-long terms and then to provide information about the precursors of the eruptions. An effective monitoring system based on the INSAR, however, cannot leave the limits discussed in the previous paragraph out of consideration.

The first point to be addressed is to set up a method to assess the quality of a particular interferogram from the atmospheric errors point of view. Above we have seen that though it is possible to evaluate, from a theoretical point of view, the contribution of the atmosphere into a generic interferogram, it is relatively difficult to quantify it in a particular image, without any independent data. Provided that the tropospheric delays measured from GPS stations are congruent with the results of models (*e.g.*, [37]) calibrated with ground-based meteorological data, as recently validated by [34], it should be possible to envisage the integration between GPS-based data with cheap and standard meteorological data, in order to make an appropriately dense grid of tropospheric delays estimation in the studied areas. This operative plan could take advantage of the existing (or planned) GPS permanent network in several active volcanic areas (*e.g.*, Hawaii, Etna, Piton de la Fournais, etc.). Furthermore, the availability of meteorological satellite images could improve the spatial distribution of the delay estimation.

The second point needed to make the INSAR operational, for monitoring ground deformations, is to attempt the integration between the ground-based measurements with the INSAR ones. This aim requires to make, from the metrological point of view, these two kinds of measurements comparable. Taking into account that the interferograms provide a mono-dimensional component of the displacements along the line of the sight direction, while the ground-based measurements may be mono-dimensional (*e.g.*, from levelling lines), two-dimensional (from EDM networks) or three-dimensional (*e.g.*, from GPS network), the only right way to face this problem is to transform the 3D GPS displacement vectors into the SAR geometry. Further wrapping procedures may be needed if the original interferograms mapping the displacements are not unwrapped. Obviously, this solution reduces the possibilities to integrate INSAR and ground-based deformation measurements, because it excludes some data sets (levelling, EDM, tilt) but, at the same time, this limitation spurs the scientists to obtain other kinds of measurement from the SAR techniques. An interesting line of research could be the determination of 3D displacements from INSAR, as already carried out for studying the glaciers [40]. No attempt has been done until now to achieve similar results in areas different from glaciers, but this surely represents a future objective for radar interferometry [41]. In a simple way we can say that the solution to this problem consists in determining an appropriate number of one-dimensional deformation patterns (achieved by conventional differential interferograms) to be combined in order to estimate the 3D-deformation. However, to successfully achieve this aim some favourable conditions are required: the investigated area must be observed from several directions of observation, the geometric and reflectivity characteristics of the observed area must be appropriate, the deformation velocity between the different acquisitions must be constant and low. Certainly, these conditions represent severe limitations for an operative use of this approach, but, once again, the availability of this data could help to set up interpretative models of how volcanoes work and so they will help the monitoring system to operate in an effective way.

As emphasised above several times, the crucial point in the operational use of INSAR interferometry is the inversion of interferograms in order to find the source/s causing the deformation. This point could be independently considered, with it respect to the previous, in the sense that it has to face this problem even if no ground-based measurements are available or it is not possible to integrate them with interferometric data. Any procedure to extract the source parameters from INSAR data may be considered operational only if it is able to manage the INSAR data in a rapid but effective manner. To approach this problem a reasonable simplification of the problem should be attempted assuming that one or two simple sources have to be searched (point pressure, ellipsoid, dislocation, etc.). Among the different strategies available to perform the inversion, the numerical methods seem to be the most promising for several reasons. First of all they do not require either the linearisation of the problem or to fixing the starting point more close to the final solution. Secondly, they are able to manage a large amount of data rapidly and in robust way even if they have heterogeneous quality. Finally, in some cases, they might be automatised (*e.g.*, by using neural networks). The advantages of such kinds of approach to solve inverse problems in ground deformation studies with respect to the least-square approach have already been proven for GPS data [42]. Furthermore, the use of simple models offer the opportunity to emphasise the effects of local sources (*e.g.*, local movements due to small faults or gravitational instability) eventually acting on the volcano, by inspecting the residual images. The possibility to detect these local effects may play an important role in the assessment of the volcanic/seismic hazard over the short-middle term.

5. – Conclusions

Volcanoes are one of the most surveyed areas by SAR and they are frequently used as test areas for INSAR applications. Several works carried out during the last decade envisaged a rapid introduction of this technique in the monitoring system of active volcanoes as well as in seismic areas. This idea was one of the main motivations for the use of SAR in Earth Observation from space and, consequently, the improvements in interferometric processing have also been tested on some active volcanoes. The first applications, however, highlighted limitations in an extensive use of INSAR techniques to survey volcanic areas and, in the cases where these data have been used to model the volcanic deformation sources, disagreements between these results and those obtained from typical geophysical and geological data have been arisen. These first partial failures (or questionable success) spurred the researchers to work around the main sources of these limitations (*e.g.*, the problems relevant to the atmospheric effects) and now it is possible to envisage a better aimed use of the INSAR in volcanology.

In the present paper the problem of the introductions of INSAR into the monitoring systems of the volcanoes is addressed. Bearing in mind the peculiarities of this application, several applications can certainly be identified. Concerning the topographic use of the interferometry, it is unlikely to be useful to quantify the volume of new volcanic products outpoured during an eruption, but it has a greater chance of being applied to mapping the areas affected by new emplacements of volcanic terrain. From a monitoring point of view, this capability has to be considered also because these results may be available daytime and night time and under any weather conditions. In general the mapping performance of the INSAR may be profitably applied to eruption detection on volcanoes located in difficult access areas.

The fields of application of the INSAR to measure ground deformations are more promising. They are candidates to help the assessment of volcanic hazard over the middle-long term, allowing to investigate the dynamics of deformation sources located at medium-deep level of the crust. However, complete achievement of this objective requires that a few problems be solved. The first is an ineluctable prerequisite and concerns the possibility to identify the effects of the changes in atmospheric characteristics between the two SAR passes and to cancel it in the interferograms. Researches carried out recently allow to envisage that an effective way to solve this problem could be the use of the tropospheric delays measured by GPS stations at the same time of the SAR passes; these data might be integrated by the delay estimated by applying atmospheric models calibrated on ground-based meteorological data. Such networks of GPS and meteorological stations are already available—or planned in the very next years—on many active volcanic areas for other geophysical purposes, and data collected by them can be certainly used to solve this problem. Another problem to be solved concerns the integration between the INSAR and other geodetic or geophysical data in order to allow a joint inversion of the data to determine the ground deformation source parameters. At this moment, the possibility to easily overcome this drawback is limited to the conversion of the 3D displacement vectors provided by GPS networks into SAR geometry. In the future, it is hoped that 3D displacements might also be provided directly by INSAR techniques. However, the many operative constraints to achieve this aim advise to carefully test this new approach by carrying out specific researches. Finally, the crucial points for an operational use of the INSAR in volcano monitoring require devising an effective and robust way to invert this data. Taking into account the peculiar characteristics of the interferograms (large amount of data, heterogeneous quality of the data set, etc.) the most promising approach seems that based on the use of numerical methods. This approach will allow to make the processing of ground deformation source searching automatic, if simple source models are adopted; in view of the integration of INSAR data in an operative monitoring system, this possibility seems to be more attractive.

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